Design of Pipelines Against Ice Scour: Effects of Seabed Geology

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Abstract

In recent years, several computational models were published for the analysis of pipelines subjected to ice scour. With one exception, most of these models assumed uniform seabed soil properties. This paper studies the effects of different seabed soil stratigraphies on the ice scour process. Influence of various stiffer and softer soil sequences on the pipeline stresses are analyzed. Effects of reworking or remolding of soils by recurrent scours are studied. The question of existence of limiting scour depths is explored by examining the interaction forces between the seabed soils and the ice keel during the scour process.

Keywords

Pipelines; Ice Scour; Finite Element Method

Introduction

Simulation of large deformation soil mechanics problems has now become possible with the development in numerical methods specifically in Finite Element (FE) method in particular Arbitrary Lagrangian-Eulerian (ALE) methods. Since the publication of the first paper applying this method to the ice scour problem (Konuk and Gracie, 2004), many papers appeared in the literature. A recent review can be found in Konuk (2009). With the exception of Konuk et al (2005), all of these publications assumed a homogenous soil mass. In Konuk et al. (2005), an ice scour problem is studied with two different soil media, one representing the seabed soils and the other representing the infill material in the pipeline trench.

It is known that in many locations, the seabed is made up of several geological strata with significantly distinct properties. For example, in most locations in the Beaufort Sea, the seabed surface sediments can be characterized by an ice scoured Holocene unit overlying Pleistocene sequences (See Becker et al. 2006, Phillips et al. 1991 and Foster 1988). The differences in soil properties between different strata are especially pronounced on the continental shelf of Alaska where

the Pleistocene layer is closer to the seabed. This paper is an attempt to understand the potential effects of different geological strata on the stresses experienced by pipelines installed (buried) in such locations during an ice scour event. The paper also investigates the importance of the recurrent reworking or remolding of the seabed soils on the response of the pipeline by using destructuration theory. The second objective of this paper is to study the relationship between ice scour depths and the soil stratigraphies.

The Ice Scour Process and Finite Element Model

Ice ridges form during the collision of the floating ice floes or more often when the thinner ice formed in the leads between the ice floes getting crushed when the floes move towards each other. In time, freeze-bonds begin to form between the ice fragments in the ice rubble constituting the ridge. At the same time, due to exposure to colder temperatures, the sea water within the upper layers of the ridge begins to freeze and forms the consolidated layer as illustrated in Figure 1. Depending on the age of the ridge, ridge strength and mechanical properties may vary. Eventually, the first-year or multi-year ridges get frozen-in within larger floes. When the ice floes move towards shallower waters due to wind or current forces, one or some of the deeper ridges contact the seabed. Although there are no recorded observations, it is postulated that during the initial phase of this interaction, the ice ridge keel may deform or small fragments may break off from the ridge keel due to the interaction forces induced by the seabed. However, many scours recorded in the Beaufort Sea indicate that once the scour depth reaches a significant magnitude, the ice ridge keel appears to remain intact and the scour depth and profile remain nearly constant until a limit driving force is reached or the parent floe somehow comes to a stop.

Figure 1 illustrates the mechanics of the ice ridge and seabed soil interaction. It is assumed that the ice ridge locked into a large ice floe does not experience any rotational rigid body motions. However, it is allowed to move in the vertical direction during a scour event in order to maintain equilibrium between the soil forces and the ice ridge weight (and buoyancy). As shown in Figure 1, in this paper, the ice ridge geometry is idealized as a truncated cone.
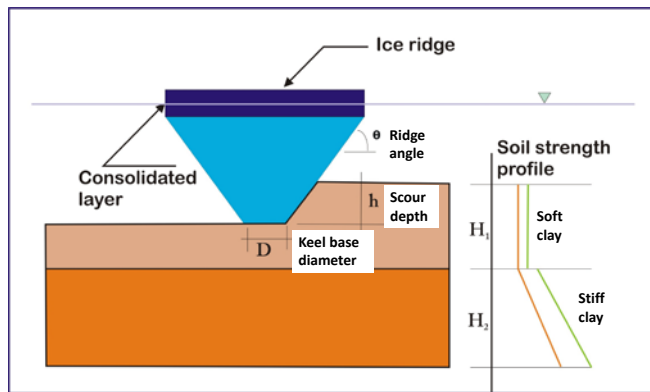

FIG. 1 ILLUSTRATION OF THE ICE SCOUR PROCESS FOR A STRATIFIED SEABED

The seabed geology is assumed to be formed from stiff clay overlaid with 2.5 m thick softer clay. Variation of the soil strength or soil characteristics as a function of depth is approximated by a linear function. In Figure 1, continuous and discontinuous soil profiles are illustrated by the colored (orange and green) lines on the right.
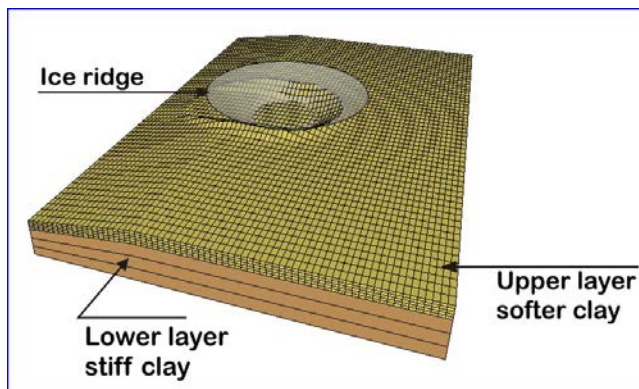

FIG. 2 ILLUSTRATION OF THE FINITE ELEMENT MODEL

In this paper, the ice scour model developed by Konuk and Gracie (2004), Konuk et al. (2005), Konuk and Yu (2007). and Konuk (2009) is used with some modifications. The model which is shown in Figure 2 consists of a soil tank with dimensions of length 100 m, width 70, and height 10 m. The model contains a short slope along its width to allow for a smooth start for the scour process. The upper soft clay unit with height of

2.5 m (H_1) is divided into two layers. The first layer represents the disturbed weak soil reworked repetitively by multiple scour events. The second layer within the upper unit represents the remaining undisturbed part of the top soft clay soil. In the current model, the stiffer lower layer soil with height of 7.5 m (H_2) is divided into three layers with linearly varying properties as a function of depth. CAP constitutive model is used to model both soil units. The remolded soil properties are characterized using destructuration theory presented by Cudny and Vermeer (2004).

The total number of soil layers including two layers for the upper soft clays and three layers to represent the lower stiffer clays, is therefore five. Detailed properties of these five soil layers are given in Table 1. In the FE model, the ice ridge is modeled as a rigid body. As mentioned above, its geometry is taken as a truncated cone. The keel base diameter of the ice ridge is taken as 15 m. The slope of the ice ridge from the horizontal is 30 degrees in all the runs presented in this paper.

TABLE 1 SOIL PROPERTIES

Layer Number from Top	Layer Description	Bottom elevation (m)	Theta (θ)	Alpha (α) (Pa)
1	Disturbed upper clay	1, 1.5, 2.0	0.05	500
2	Undisturbed upper clay	2.5	0.05	1000
3	Stiffer Layer 1	5.0	0.5	1000
4	Stiffer Layer 2	7.5	0.5	6000
5	Stiffer Layer 3	10.0	0.5	11000

Parametric studies are carried out to determine the influence of the depth of reworked soils and also the ice scour or keel depth. The fourteen (14) cases run for this paper are listed in Table 2. In this table, two values are given for ice scour depth. The lower values indicate the actual scour depth while the higher values shown in parenthesis provide the keel depths with respect to the original soil surface before the soils are allowed to consolidate and settle. Case 0 is the base case corresponding to an ice scour depth of 1.5 for a totally undisturbed soil mass, whereas, in Case 4, a scour depth of 3 m is applied to a seabed with a 2 m deep reworked softer upper layer clay.

TABLE 2. ICE SCOUR CASES ANALYZED

Case Namer	Disturbed soil depth (m)	Ice Scour Depth (before settlement) (m)	Theta for disturbed soil (θ)	Alpha for disturbed layer (α) (Pa)
Case 0	0	1.5 (1.7)	0.05	1000
Case 1.A	1	1.5 (1.7)	0.05	500
Case 1.B	1.5	1.5 (1.7)	0.05	500
Case 1.C	2	1.5 (1.7)	0.05	500
Case 2.A	1	2 (2.2)	0.05	500
Case 2.B	1.5	2 (2.2)	0.05	500
Case 2.C	2	2 (2.2)	0.05	500
Case 3.A	1	2.5 (2.7)	0.05	500
Case 3.B	1.5	2.5 (2.7)	0.05	500
Case 3.C	2	2.5 (2.7)	0.05	500
Case 4.A	2	3 (3.2)	0.05	500
Case 6.A	0	1.8 (2.0)	0.05	1000
Case 6.B	0	1.8 (2.0)	0.05	6000
Case 6.C	0	1.8 (2.0)	0.1	1000

Note: The soil parameters given for Cases 6 are for the harder lower clay layer.

A version of the model with the pipeline buried just below the top soil layer was also created. This model was run for three different lower soil unit properties (Cases 6A, 6B, 6C).

Ice Scour Model Results

As indicated above, the FE model was exercised for different remolded soils states in conjunction with a stiffer lower strata and different scour depths. Figures 3 and 4 show the total vertical and horizontal forces generated by the scoured seabed for Cases 0 and 4.A.
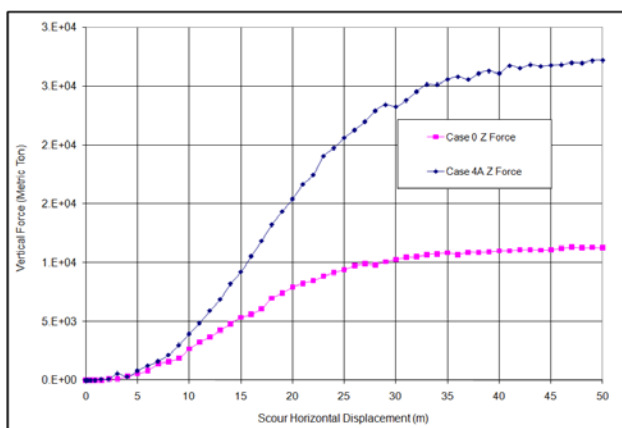

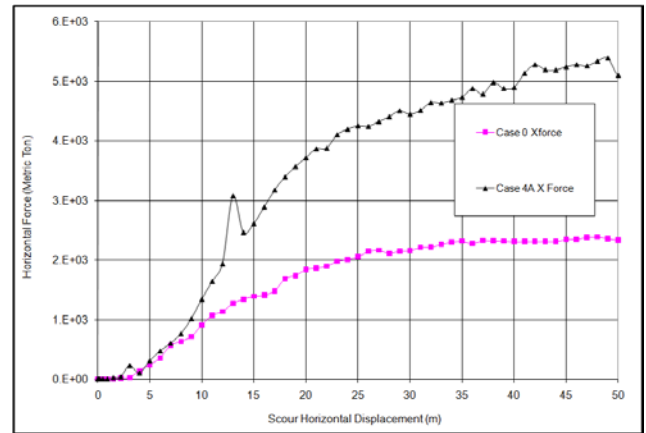FIG. 3 VERTICAL SCOUR FORCE HISTORIES FOR CASES 0 AND 4

FIG. 4 SCOUR FORCE HISTORIES FOR CASES 0 AND 4

In Figure 5, the maximum vertical scour forces are plotted against the scour depth. This figure shows a rapid increase in vertical forces when scour depths exceeds 2 m. Figure 6 and 7 present the maximum vertical and horizontal scour forces versus remolded soil layer depth. These figures show that the scour forces reduce initially as the remolded soil depth increases. However, when the scour depth is close to or higher than the remolded soil depth, the forces come back close to the original levels.
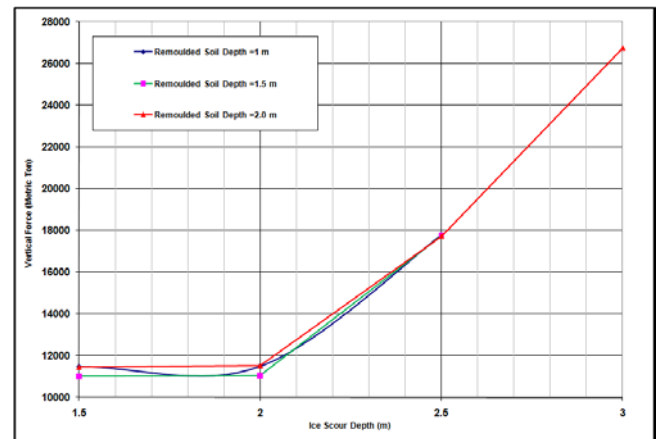

FIG. 5 VERTICAL SCOUR FORCE VS. SCOUR DEPTH FOR DIFFERENT REWORKING DEPTHS

Figures 8 and 9 present the pipeline scour mid-point trajectories for Case 6.A, 6.B, and 6.C which indicate the influence of the lower stiffer clay layer properties. In Cases 6.A and 6.B, the hardening parameter (friction angle) is lower than Case 6.C. For both of these lower hardness (friction angle) lower layer cases, the pipeline rebound is more pronounced than the Case 6.C. In the same way, the pipeline stresses are significantly lower for the Case 6.C (the maximum stress is reduced by 25%) indicating that the presence of harder or stiffer layer below a softer top soil unit can be beneficial for the protection of pipelines from ice scour.
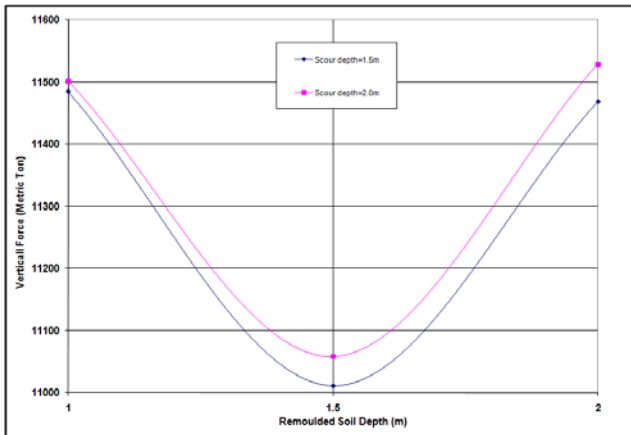
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FIG. 6 VERTICAL SCOUR FORCE VS. REMOLDED SOIL DEPTH FOR DIFFERENT SCOUR DEPTHS
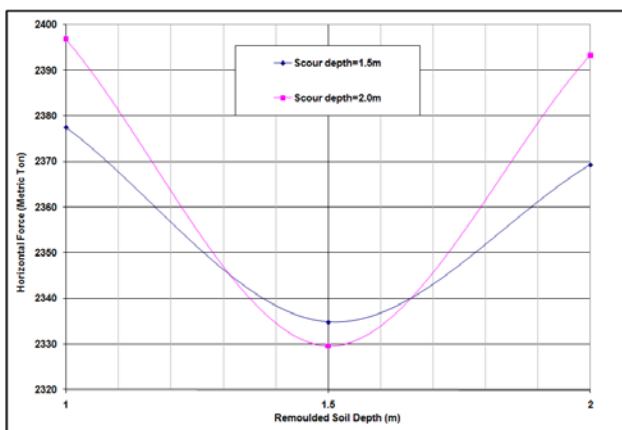

FIG. 7 HORIZONTAL SCOUR FORCE VS. REMOLDED SOIL DEPTH FOR DIFFERENT SCOUR DEPTHS
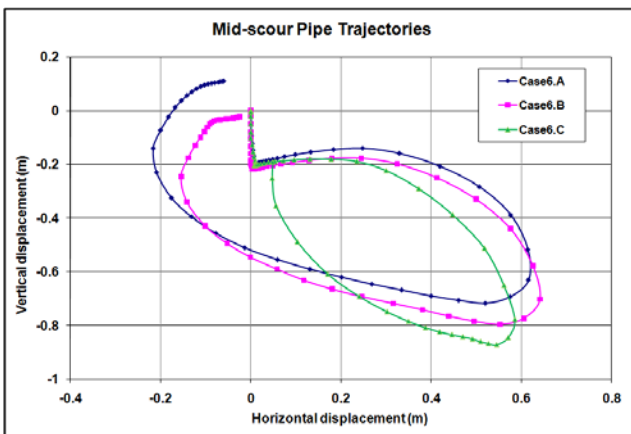

FIG. 8 MID-SCOUR PIPE DISPLACEMENT TRACES

In Figure 10, outputs from the ice scour model with the pipeline are shown at three different instances. The top soil layer color fringes indicate plastic strains. Comparison of the plastic strains near the pipeline which is the highest in the second frame is made in this figure when the ice ridge edge is closest to the pipeline. It can be seen from Figure 10 that the pipeline experiences the highest displacements in the direction of the ice travel at this instance.
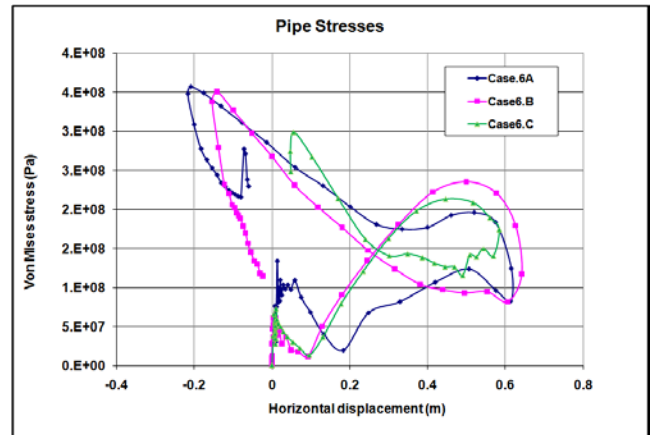

FIG. 9 MID-SCOUR PIPE STRESSES AT 3 O'CLOCK POSITION

Soil Charcterization Using Penetration Tests

Simulation of in-situ soil tests such as T-bar or Cone Penetration (CP) tests by an FE model incorporating stratigraphy similar to the ice scour model is to be utilized for deriving and validating the CAP constitutive model soil parameters. This section is intended to demonstrate this methodology for deriving the soil constitutive parameters. Although no site specific data is used, the soil characteristics used in this paper are similar but more conservative than soils found in general offshore Alaska where the strength differences between Pleistocene and Holocene are typically more pronounced than the values used here.
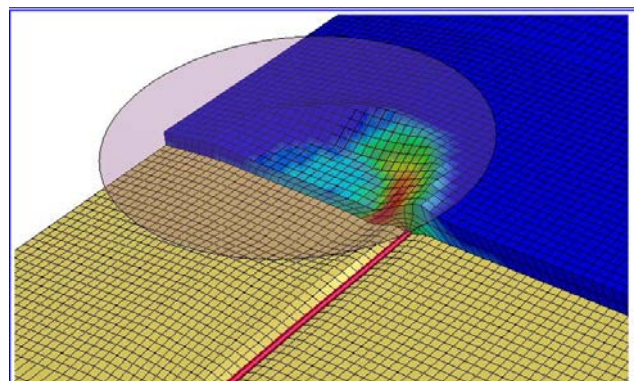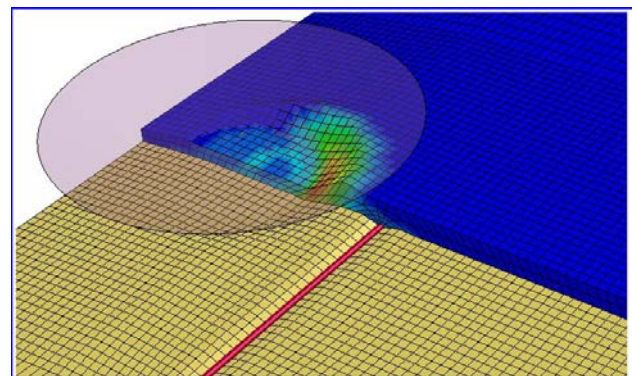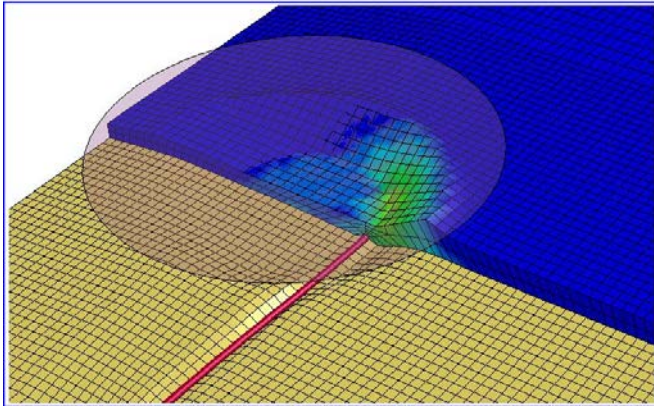
FIG. 10 OUTPUT FROM THE TWO LAYER ICE SCOUR MODEL
WITH PIPE AT DIFFERENT SIMULATION TIMES (30 SEC, 35 SEC,
AND 40 SEC)

Figure 11 shows the output from the in-situ (penetration) test FE model developed for the calibration of soil parameters. In this case, Figure 11 illustrates the process of a 16 inch pipe penetrating into the soil at different stages of the test. In Figure 12, resistance versus penetration distance is plotted. As it can be seen from this figure, the resistance force starts increasing well before the pipe indentor actually contacts the harder bottom soil layer. In Figure 12, the location of the interface between the top and bottom soils layers after the consolidation process is shown by the vertical red line.

An inverse method is utilized to derive the soil constitutive parameters. By following an iterative procedure, the soil parameters are determined by matching the actual in-situ test graphs with the results from the FE simulation model of the in-situ tests. Figure 12, illustrates the resistance plot for the soils modeled in the ice scour studies presented in this paper. The actual soil constitutive parameters used in this paper are given in Appendix A for the base case (Case 0).
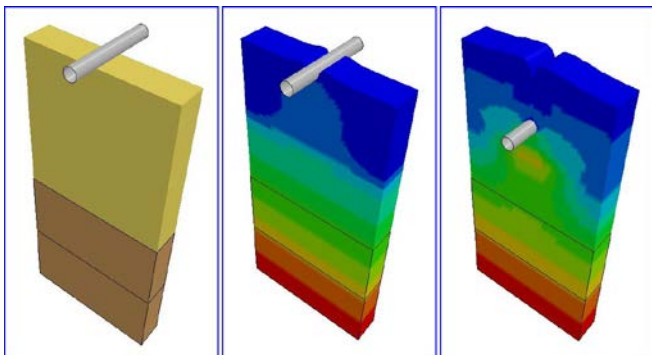
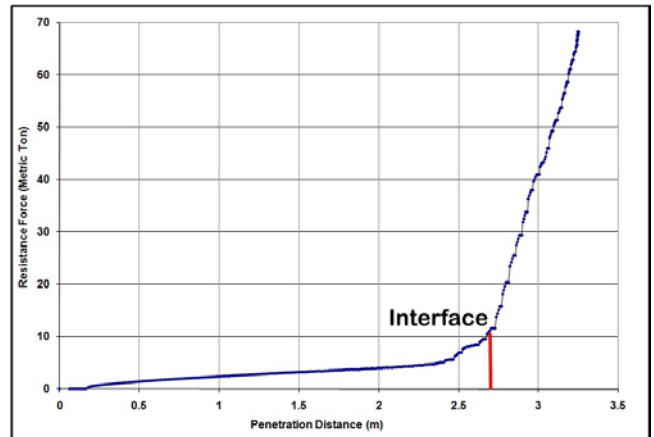

FIG. 11 SIMULATION OF IN-SITU PIPE PENETRATION TESTS

FIG. 12 RESISTANCE VS. PENETRATION

Soil And Ice Ridge Interaction

In order to assess the feasibility or likelihood of a given scour, a preliminary parametric study of ice ridge (rigid body) forces is studied. Assuming that the ice ridges are free floating before the seabed scour is initiated, the forces required to scour the seabed has to be balanced with the surcharge or the vertical force ice keel can occur. The vertical force applied by the ice
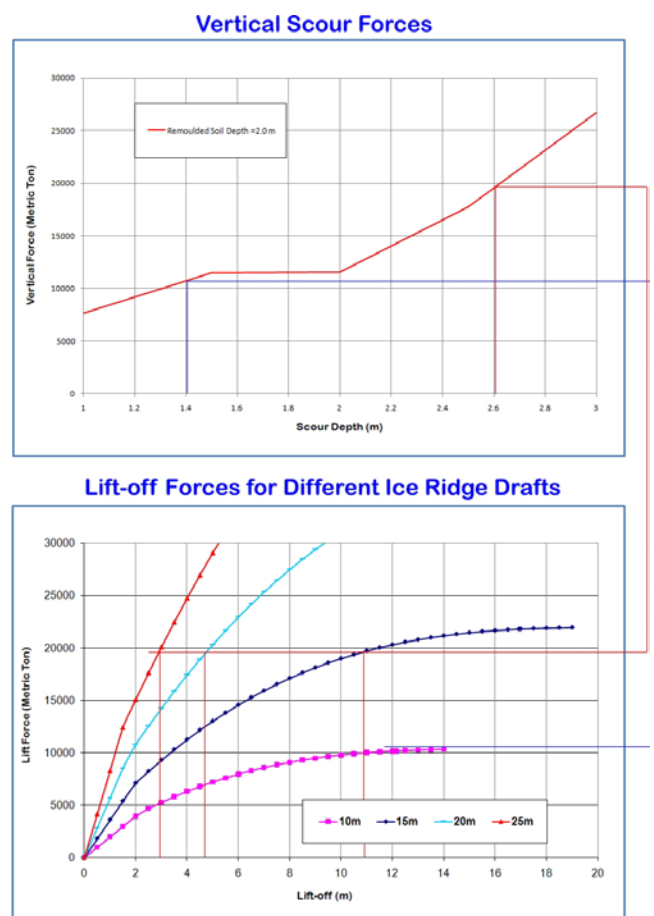

FIG. 13 (A) VERTICAL ICE SCOUR FORCES, (B) ICE RIDGE LIFT-
OFF FORCES

ridge is derived by subtracting the buoyancy forces from its total weight. Figure 13 (b) includes the graphs of ice ridge lift-off force versus the lift-off elevation for a conical ice ridge. The properties of the ice ridges considered in this study are given in Table 3.

Since the vertical soil and ridge forces have to be in equilibrium, Figures 13a & 13b can be used to determine the conditions for a certain ridge to generate a certain depth scour. The methodology is illustrated with examples in Figures 13a and 13b. For example, from Figures 13a and 13b, it can be observed that for the given seabed soil properties and geology, an ice ridge of 10 m draft cannot generate scours deeper than 1.4 m. On the other hand, an ice ridge with 20 m draft will need to travel sufficient distance to encounter a 4.7+2.6=7.3 m bathymetry (seabed elevation) change to be able to generate a 2.6 m scour (Figure 13a). The 4.7 m is the magnitude of lift-off required to generate the required vertical force.

Discussion and Conclusions

Combining past experiences and published results with the results presented in this paper, it can be observed that the soil stratigraphy has a very significant influence on the scour forces generated by the seabed soils. Although more parametric studies are required to confirm this, the presence of the hard clay layer underneath a soft layer causes the vertical scour forces to increase at a geometric rate. At the same time, hard lower layer causes the reduction in pipeline stresses and displacements.

A methodology is presented in this paper to model the degradation or variance of soil parameters due to the effect of repetitive reworking of seabed soils using destructuration theory. However, the preliminary and limited results obtained in this study with respect to the influence of the reworking due to repetitive scours are not conclusive.

TABLE 3 ICE RIDGE PROPERTIES

Ridge Property	Value	Units
Draft	10-30	m
Keel Base Diameter	15	m
Ridge Angle	30	Degrees
Consolidated Layer Thickness	3	m
Ice Density	920	Kg/m³
Density of Consolidated layer	828	Kg/m³
Keel Porosity	35	%
Sea Water Density	1024	Kg/m³

The procedure developed in this paper to combine the soil forces with the ice ridge mechanics suggests several promising conclusions and trends. The following lists the main conclusions:

(1) There is a unique limit scour depth which cannot be exceeded by an ice ridge of a given draft.

(2) In order to achieve a certain ice scour depth, an ice ridge of given draft will be needed to travel a certain distance to encounter a minimum bathymetry (elevation) change.

(3) Presence of a stiffer lower soil unit below pipeline burial depth could reduce the pipeline stresses; thus requiring a less burial depth than it would be required otherwise.

(4) A site with a thinner softer unit above stiffer lower soil strata should experience shallower scours than a site with thicker soft clay unit above or a site with no stiff unit when the ice conditions are the same will experience.

Since the ridge travel distances depend on the global interaction of ice floes in the winter seasons, several additional corollaries of the second conclusions can be drawn:

(5) A site with milder bathymetry changes (slope) is less likely to experience deeper scours.

(6) Deeper scours are more likely to be observed in areas with more rapid bathymetry changes or deeper waters where the initial ice ridge drafts are likely to be higher.

(7) Deeper scours are more likely to be generated during the ice break up period when ice floes have more freedom to move around.

In order to confirm and verify the last three observations and conclusions, additional studies and more comprehensive ice ridge data and information on ice floe drift trajectories would be required.

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APPENDIX A

In Table 4, the base case soil CAP constitutive law parameters are listed. The notation used here is similar to the notation used by Simo (1988).

TABLE 4 SOIL CAP CONSTITUTIVE MODEL PROPERTIES

Parameter	Definition	Base Case Value
ϱ	Density	1400 Kg/m^3
K	Bulk Modulus	10 MPa
G	Shear Modulus	1 MPa
α	CAP Parameter	1000 Pa
γ	CAP Parameter	0.0 Pa
β	CAP Parameter	0.0 Pa^{-1}
θ	CAP Hardening Parameter	0.05
R	CAP Parameter	4.0
W	CAP Parameter	0.06
D	CAP Parameter	1.26 E-06 Pa^{-1}